Radiation Report

OPA4H199-SP Single-Event Effects (SEE) Radiation Report

ABSTRACT

The purpose of this study is to characterize the single-event effects (SEE) performance due to heavy-ion irradiation of the OPA4H199-SP. Heavy-ions with LET_{EFF} of 65 MeV × cm^2 / mg were used to irradiate four production devices. Flux of approximately 10^5 ions/cm^2 × s and fluence of 10^7 ions / cm^2 per run were used for the characterization. The results demonstrated that the OPA4H199-SP is SEL-free up to 65 MeV·cm^2/ mg at T = 125°C. The output signal, V_{OUT}, (5% window) was monitored to check for transients and SEFIs. The results showed the device is SET free up to 65 MeV × cm^2/ mg at T = 25°C.

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1 Introduction

The OPA4H199-SP is a 40V operational amplifier and is optimized for use in a space environment. The device offers exceptional DC precision and AC performance, including rail-to-rail input/output, low offset (±125μV, typ), low offset drift (±0.3μV/°C, typ), low noise (10.8 nV/√Hz and 1.8μVPP), and 4.5MHz bandwidth.

The wide voltage range of the OPA4H199-SP enables the device to be used in low voltage domains, such as 3.3V and 5V, or higher voltage ranges up to 40V. Unique features such as differential and common-mode input voltage range to the supply rail, high output current (±75mA), high slew rate (21V/μs), and high capacitive load drive (1nF) make the OPA4H199-SP a robust, high performance operational amplifier for high-voltage space applications.

The OPA4H199-SP is available in a small-sized, radiation-hardened plastic, 14-pin SOT-23 (DYY) package. The SOT-23 (DYY) package has a body size that is less than 1/5th of the size of traditional 14-pin ceramic packages. The OPA4H199-SP is specified from –55°C to 125°C.

Table 1-1. Overview Information

Description (1)	Device Information
TI Part Number	OPA4H199-SP
Orderable Number (SMD Number)	5962R2321401PXE
Device Function	Operational Amplifier (Op-amp)
Technology	LBC9 (Linear BiCMOS 9)
Exposure Facility	Radiation Effects Facility, Cyclotron Institute, Texas A&M University
Heavy Ion Fluence per Run	1.00×10^6(SET) – 1.00×10^7 (for SEL and SET) ions / cm^2
Irradiation Temperature	25°C (for SET testing) and 125°C (for SEL testing)

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2 Single-Event Effects (SEE)

The primary concern for the OPA4H199-SP is the robustness against the destructive single-event effects (DSEE): single-event latch-up (SEL). In mixed technologies such as the BiCMOS process used on the OPA4H199-SP, the CMOS circuitry introduces a potential for SEL susceptibility.

SEL can occur if excess current injection caused by the passage of an energetic ion is high enough to trigger the formation of a parasitic cross-coupled PNP and NPN bipolar structure (formed between the p-sub and n-well and n+ and p+ contacts) [1] [2]. The parasitic bipolar structure initiated by a single-event creates a high-conductance path (inducing a steady-state current that is typically orders-of-magnitude higher than the normal operating current) between power and ground that persists (is *latched*) until power is removed, the device is reset, or until the device is destroyed by the high-current state. The OPA4H199-SP was tested for SEL at the maximum recommended supply voltage of 40V. The input common-mode voltage (V_{IN}) was set to be equal to the supply voltage during testing. The device was configured as a buffer amplifier with the output pin connected to the inverting input pin. During testing of the devices, the OPA4H199-SP did not exhibit any SEL with heavy-ions with LET_{EFF} = 65MeV × cm^2 / mg at flux of approximately 5 × 10^4 ions / cm^2 × s, fluence of approximately 10^7 ions / cm^2, and a die temperature of ~125°C.

Another concern on high reliability and performance applications is the single-events-transient (SET) characteristic of the device. The OPA4H199-SP SET performance was characterized up to LET_{EFF} = 65MeV-cm2 /mg. The device was characterized for SET at supply voltage of 40V under DC input conditions. Test conditions and results are discussed in Table 8-2.

3 Device and Test Board Information

The OPA4H199-SP is packaged in a 14-pin plastic SOT-23-THIN (DYY) package as shown in Figure 3-1. The AMP-PDK-EVM evaluation module (EVM) was used to evaluate the performance and characteristics of the OPA4H199-SP under heavy ion radiation. The OPA4H199-SP devices were decapsulated to reveal the bare die face for all heavy-ion testing. The device under test (DUT) was inserted into a socket into the AMP-PDK-EVM in order to test various units with the same EVM. Each device was configured in a buffer configuration. For more information about the AMP-PDK-EVM evaluation module, click here.

Figure 3-1. Photograph of OPA4H199-SP

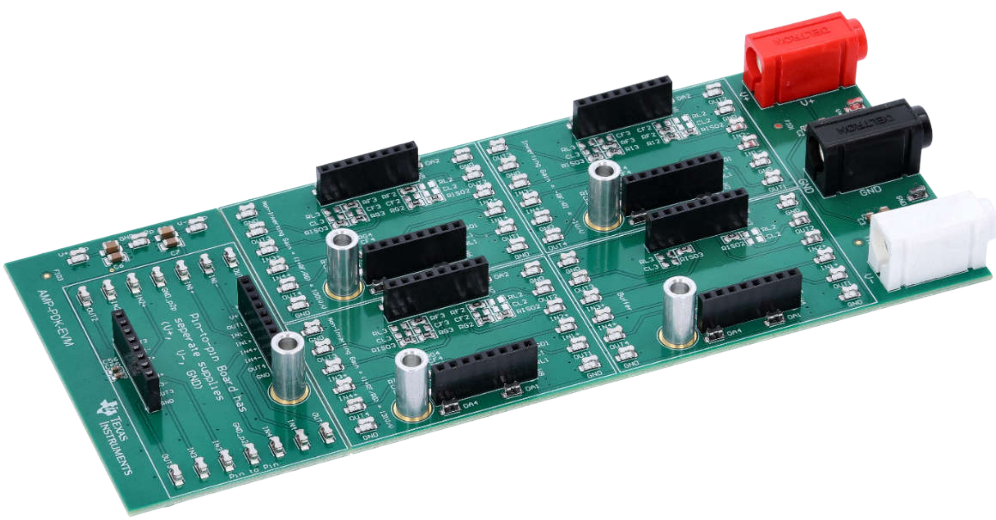

Figure 3-2. AMP-PDK-EVM Evaluation Module Used for OPA4H199-SP SEE Testing Top View

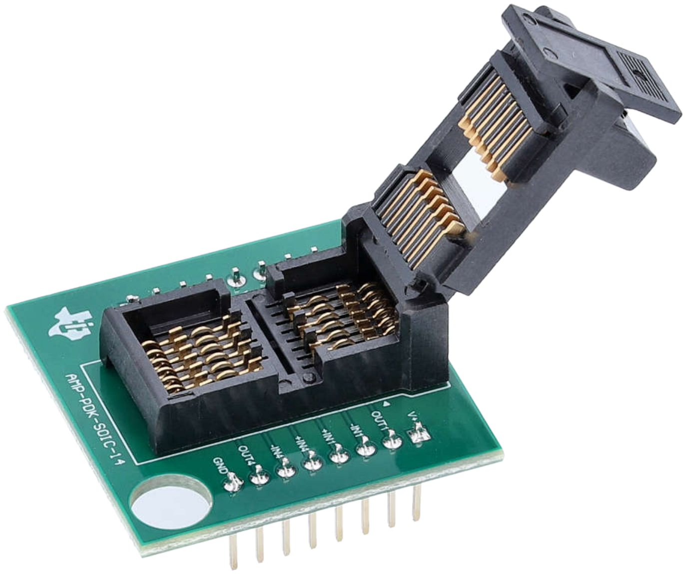

Figure 3-3. AMP-PDK-EVM Socket Angled View

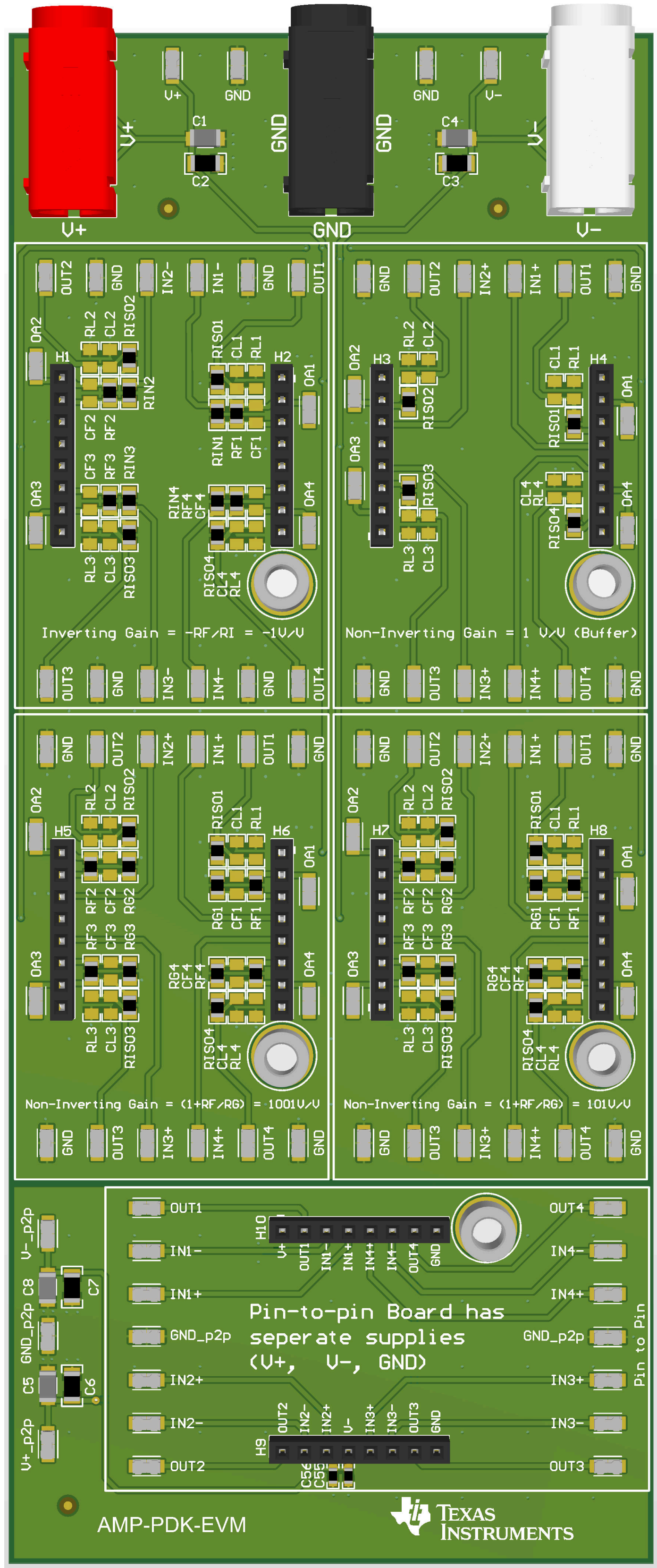

Figure 3-4. AMP-PDK-EVM Board

4 Irradiation Facility and Setup

The heavy-ion species used for the SEE studies on this product were provided and delivered by the TAMU Cyclotron Radiation Effects Facility using a superconducting cyclotron and an advanced electron cyclotron resonance (ECR) ion source. At the fluxes used, ion beams had good flux stability and high irradiation uniformity over a 1in diameter circular cross-sectional area for the in-air station. Uniformity is achieved by magnetic defocusing. The flux of the beam is regulated over a broad range spanning several orders of magnitude. For the bulk of these studies , ion flux between 10^4 to 10^5 ions/cm^2·s were used to provide heavy-ion fluences of 10^6 to 10^7 ions/cm^2.

For these experiments Praseodymium (^{141}Pr), Silver (^{109}Ag), Krypton (^{84}Kr), Copper (^{63}Cu), Argon (^{40}Ar), and Neon (^{20}Ne) were used. The angle was held to 0°, but different distances between the device and beam were used to increment the LET_{EFF}. The ^{141}Pr, ^{109}Ag, ^{84}Kr,^{63}Cu ^{40}Ar, and ^{20}Ne ions used had a total kinetic energy of 2114MeV, 1634MeV, 1259MeV, 944MeV, 599MeV, and 300MeV in the vacuum, (15MeV/amu line) respectively. Ion beam uniformity for all tests was in the range of 92 to 97%.

Figure 4-1 shows the OPA4H199 device under test (DUT) in the AMP-PDK-EVM used for data collection at the TAMU facility. Although not visible in this photo, the beam port has a 1mil Aramica window to allow in-air testing while maintaining the vacuum within the accelerator with only minor ion energy loss.

Figure 4-1. Photograph of the OPA4H199-SP EVM in Front of the Heavy-Ion Beam Exit Port at the Texas A&M Cyclotron

5 Depth, Range, and LET_{EFF} Calculation

The OPA4H199-SP is fabricated in the TI Linear BiCMOS 9 (LBC9) 130nm process with a back-end-of-line (BEOL) stack consisting of four levels of standard thickness aluminum and Damascene copper. The total stack height from the surface of the passivation to the silicon surface is 2.5μm. The decapped unit exposes the silicon to the ion radiation beam. Accounting for energy loss through the 1mil thick Aramica beam port window, the air gap, and the BEOL stack over the OPA4H199-SP, the effective LET (LET_{EFF}) at the surface of the silicon substrate and the depth was determined with the SEUSS 2020 Software (provided by the Texas A&M Cyclotron Institute and based on the latest SRIM-2013 [7] models). The results are shown in Table 5-1.

Table 5-1. Ion LET_{EFF}, Depth, and Range

ION	Angle of Incidence (°)	LET_{EFF} (MeV × cm²/mg)	Distance (mm)	FLUX (ions × cm²/mg)	Fluence (Number ions)
^{141}Pr	0	65	50	1.15×10^5	1.10×10^7
^{109}Ag	0	51	75	1.08×10^5	9.95×10^6
^{109}Ag	0	47	40	1.06×10^5	9.96×10^6
^{84}Kr	0	32	75	1.09×10^5	1.00×10^7
^{63}Cu	0	19	30	1.01×10^5	9.97×10^6
^{40}Ar	0	8	30	1.01×10^5	1.00×10^7
^{20}Ne	0	3	30	1.17×10^5	1.00×10^7

6 Test Setup and Procedures

SEE testing was performed on the OPA4H199-SP device mounted on an EVM. The device was provided power through the V+ and V- power supply pins of the device. 40V was provided to V+ and GND was provided to V- using the PXIe-4139. The OPA4H199-SP was evaluated for DC performance in a buffer configuration as shown below in Figure 6-1.

For SET testing, the common-mode input voltage was set to mid-supply (20V) and the output voltage was monitored for events using the PXIe-5172The trigger threshold for events was set to 5% of the expected output voltage (20V). Therefore, events are considered as output voltages greater than 21V or less than 19V.

For SEL testing, the common-mode input voltage was set equal to the power supply voltage of 40V. In this configuration, the quiescent current of the device was monitored and recorded using the PXIe-4139.

The power supply (PS) was controlled and monitored using a custom-develop LabView™ program (PXI-RadTest) running on a NI-PXIe-8135 controller. The DPO7254C was controlled using the front-panel interface. The DPO was left in the cave at all times, to minimize the probe cable length. A KVM extender was used to control and view the DPO from the control room at TAMU. For the SEL testing the device was heated using a convection heat gun aimed at the die. The junction temperature was monitored by using a thermal imaging camera attached as possible to the die.

Equipment Settings and Parameters Used During the SEE Testing of the OPA4H199-SP shows the connections, limits, and compliance values used during the testing. Figure 6-1 shows a schematic diagram of the setup used for SEE testing of the OPA4H199-SP.

Table 6-1. Equipment Settings and Parameters Used During the SEE Testing of the OPA4H199-SP

Pin Name	Equipment Used	Capability	Range of Values Used
V+	PXIe-4139	±60V, ±3A	40V
V-	PXIe-4139	±60V, ±3A	0V (GND)
IN+	PXIe-4139	±60V, ±3A	20V to 40V
V_{OUT}	PXIe-5172	100MS/s	—

All boards used for SEL testing were fully checked for functionality and dry runs performed to verify that the test system was stable under all bias and load conditions prior to being taken to the TAMU facility. During the heavy-ion testing, the LabView™ control program powered up the OPA4H199-SP device and set the external sourcing and monitoring functions of the external equipment. After functionality and stability had been confirmed, the beam shutter was opened to expose the device to the heavy-ion beam. The shutter remained open until the target fluence was achieved (determined by external detectors and counters).

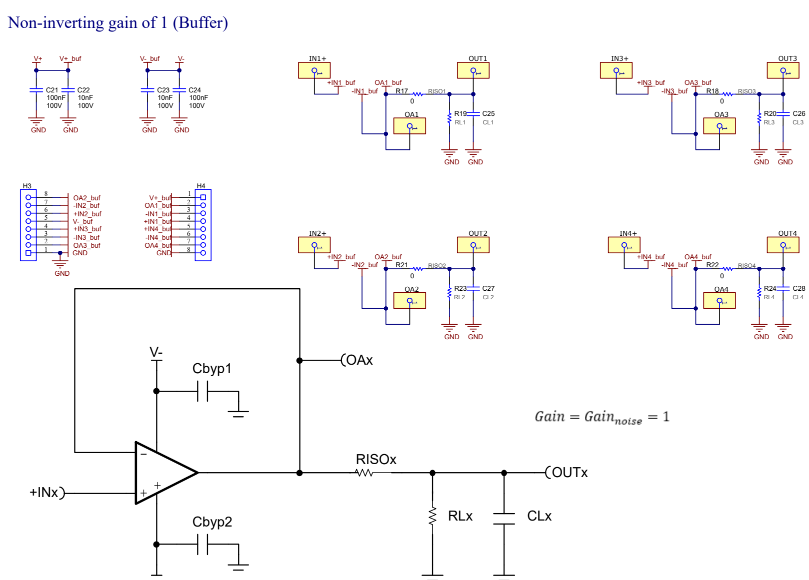

Figure 6-1. Test Configuration for the OPA4H199-SP

7 Destructive Single-Event Effects (DSEE)

7.1 Single-Event Latch-up (SEL) Results

All SEL characterizations were performed with forced hot air to maintain the die temperature at 125°C during the tests. The temperature of the die was verified using thermal camera prior to exposure to heavy ions.

The device was exposed to a Praseodymium (Pr) heavy-ion beam incident on the die surface at 0°. The distance between the device and the beam was adjusted to achieve an effective LET of 65MeV-cm^2/mg. A flux of 10^5 ions/cm^2 -s and fluence of 10^7 ions/cm^2 per run was used in all runs. The device was powered with voltage of 40V.

Run duration to achieve this fluence was approximately ninety seconds. The four devices were powered up and exposed to the heavy-ions using the maximum recommended supply voltage of 40V. The device was configured as a buffer amplifier, with the output connected to the inverting input, and the common-mode voltage was set to 40V, which is the maximum recommended input voltage. No SEL events were observed during all four runs, indicating that the OPA4H199-SP is SEL-free up to 65MeV × cm^2/mg. Table 7-1 shows the SEL test conditions and results.

Table 7-1. Summary of OPA4H199-SP SEL Test Condition and Results

Run #	Unit #	Ion	LET_{EFF} (MeV × cm^2/mg)	Flux (ions × cm^2/mg)	Fluence (Number ions)	Temperature (°C)	Distance (mm)	SEL (# Events)
23	8	^{141}Pr	65	1.21×10^5	0.99×10^7	125	50	0
24	8	^{141}Pr	65	1.24×10^5	5.06×10^6	125	50	0
25	9	^{141}Pr	65	1.23×10^5	1×10^7	125	50	0
26	9	^{141}Pr	65	1.22×10^5	4.96 x 10	125	50	0
27	10	^{141}Pr	65	1.23×10^5	1×10^7	125	50	0
28	10	^{141}Pr	65	1.25×10^5	5.01×10^6	125	50	0

Using the MFTF method shown in *Single-Event Effects (SEE) Confidence Interval Calculations* and combining (or summing) the fluences of the four runs at 125°C (4×10^7), the upper-bound cross-section (using a 95% confidence level) is calculated as: $\sigma_{SEL} \leq 9.22 \times 10^{-8}$ cm^2/ device for LET_{EFF} = 65MeV × cm^2/ mg and T = 125°C.

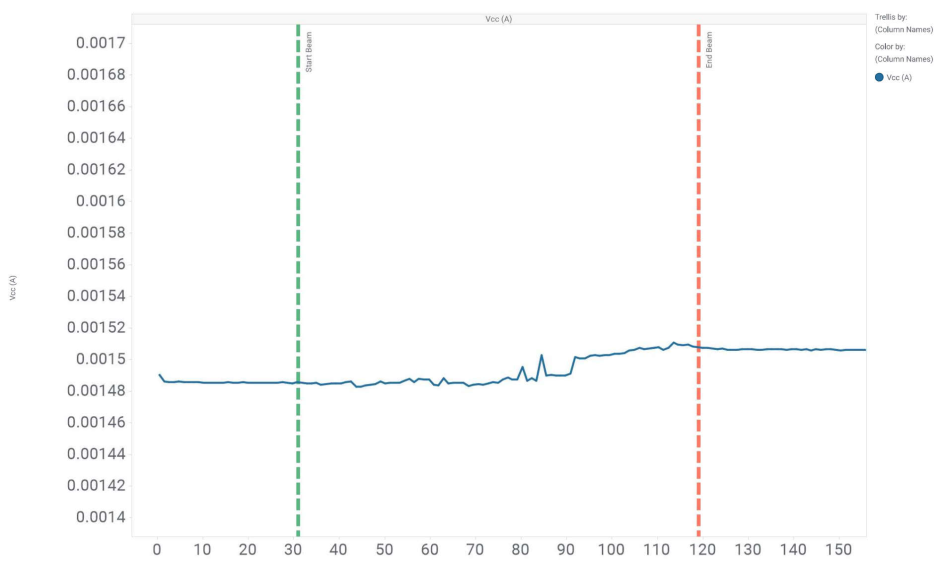

Figure 7-1. SEL Quiescent Current versus Time for Unit #8 of OPA4H199-SP LET_{EFF} = 65MeV × cm^2/ mg and Fluence = 1 x 10^7

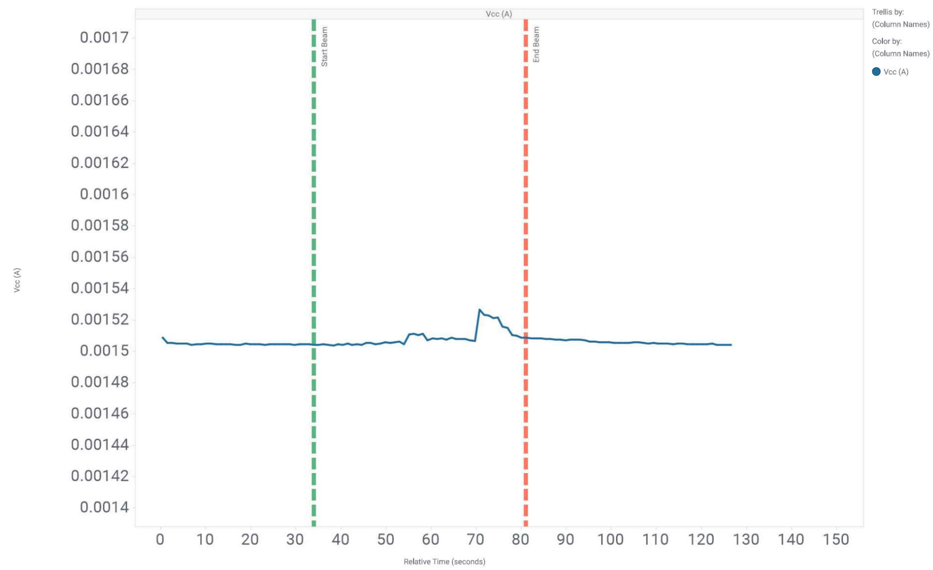

Figure 7-2. SEL Quiescent Current versus Time for Unit #8 of OPA4H199-SP LET_{EFF} = 65MeV × cm^2/ mg and Fluence = 5 x 10^6

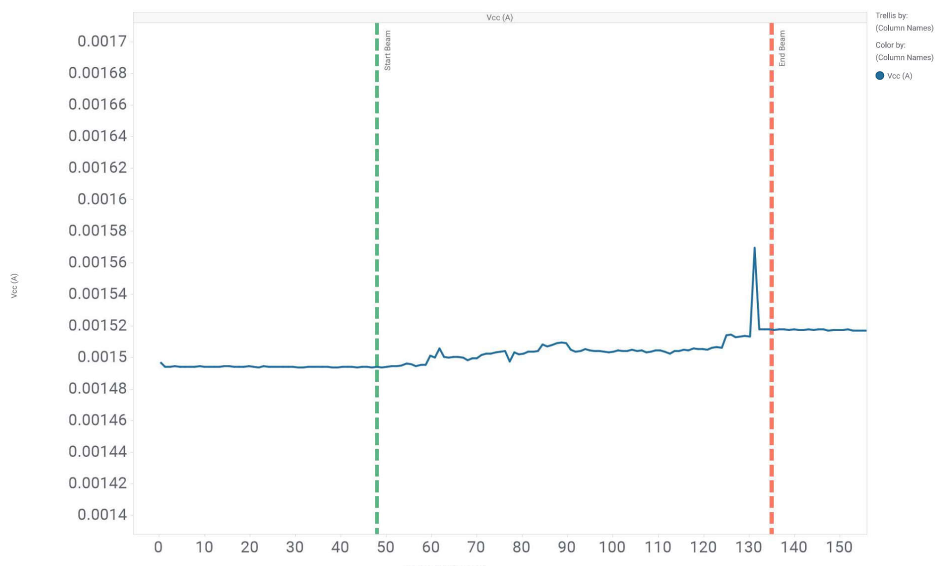

Figure 7-3. SEL Quiescent Current versus Time for Unit #9 of OPA4H199-SP LET_{EFF} = 65MeV × cm^2/ mg and Fluence = 1 x 10^7

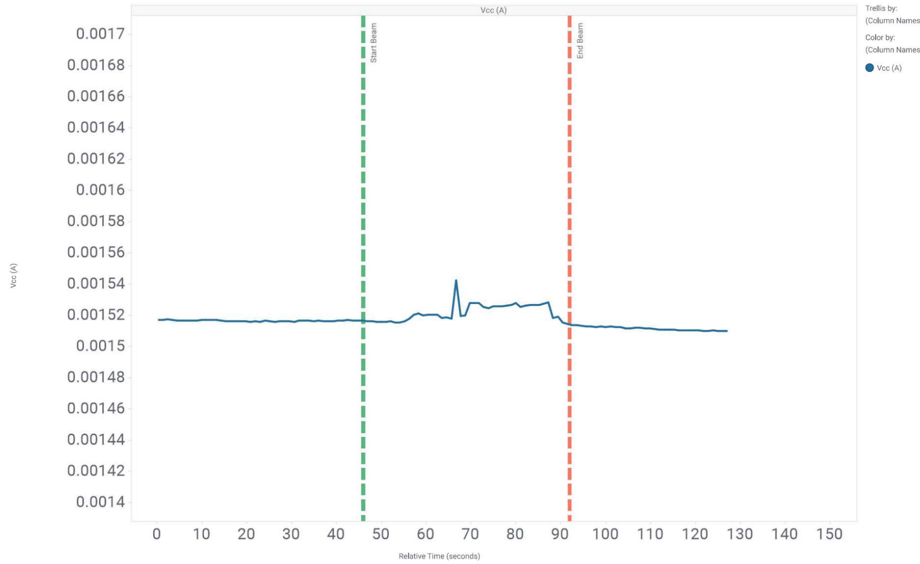

Figure 7-4. SEL Quiescent Current versus Time for Unit #9 of OPA4H199-SP LET_{EFF} = 65MeV × cm^2/ mg and Fluence = 5 x 10^6

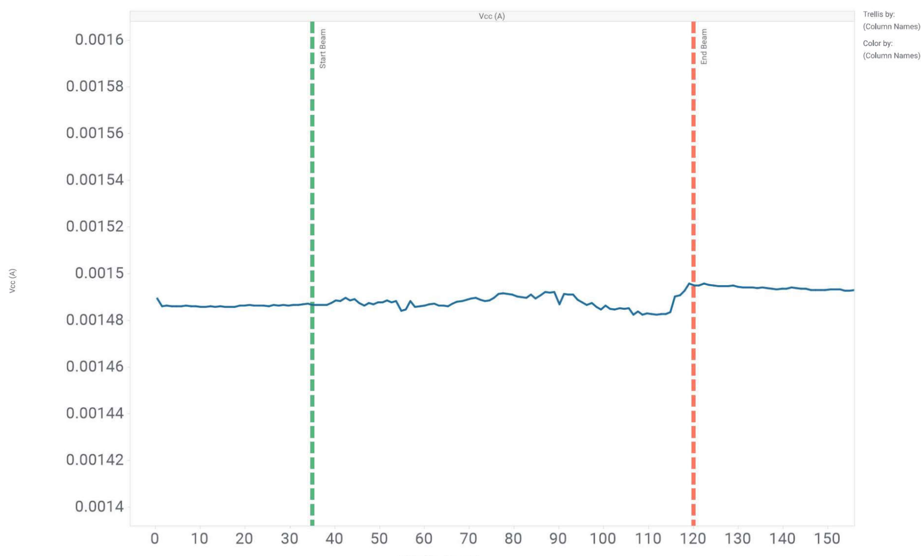

Figure 7-5. SEL Quiescent Current versus Time for Unit #10 of OPA4H199-SP LET_{EFF} = 65MeV × cm^2/ mg and Fluence = 1 x 10^7

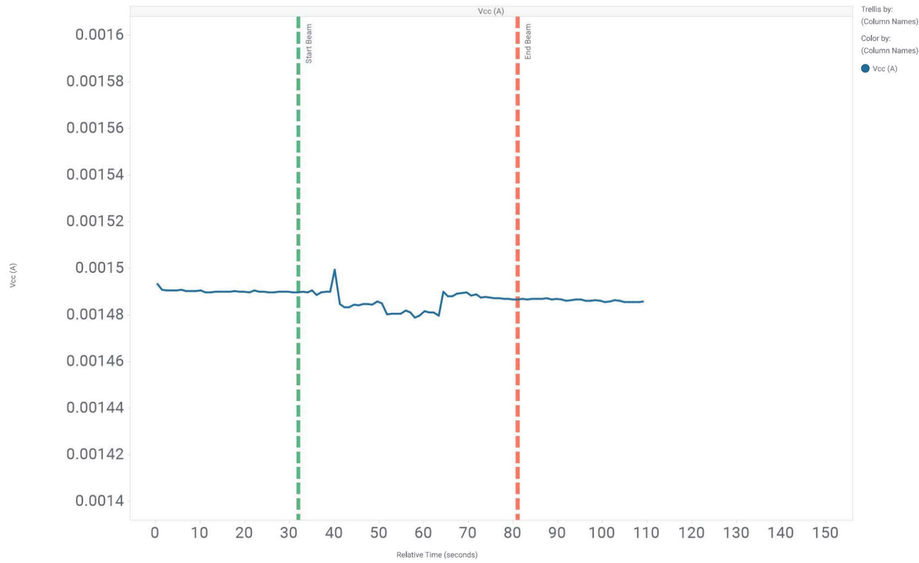

Figure 7-6. SEL Quiescent Current versus Time for Unit #10 of OPA4H199-SP LET_{EFF} = 65MeV × cm^2/ mg and Fluence = 5 x 10^6

8 Single-Event Transients (SET)

The OPA4H199-SP was characterized for SETs from 2.71MeV-cm2 /mg to 65MeV-cm2 /mg (Table 8-1 provides more information) at 40V supply voltage. The device was tested at room temperature for all SETs runs. OPA4H199-SP devices were thinned for proper heavy-ion penetration into the active circuits. Average flux of 10^5 ions/cm^2-s and fluences of 10^7 ions/cm^2 per run were used during the heavy ion characterization. The devices were tested under static (DC) inputs. The SETs discussed on this report were defined as output voltages excursion that exceed a window trigger set on the DPO7104C. The OPA4H199-SP was connected to a 40V supply and configured as a buffer with the comomon-mode input voltage set to 20V (midsupply). The output voltage was monitored directly to detect events. Test conditions used during the testing are provided in Table 8-1. Positive and negative upsets excursions were observed under DC test. The events were divided into short events and long events, based on the length of their duration before resolving back to the expected value. Figure 8-2 and Figure 8-2 are examples of long SET events. Figure 8-2 and Figure 8-2 are examples of long SET events. For each upset the maximum, minimum and transient recovery time was recorded. Weibull-Fit and cross section for the DC tests are shown in Figure 8-1 and Figure 8-2. The Weibull equation used for the fit is shown in Equation 1, and parameters are provided in Table 8-2. To calculate the cross section values at the different supply voltages the total number of upsets (or transients) and the fluences where combined (add together) by LETEFF to calculate the upper bound cross section (as discussed in Appendix B) at 95% confidence interval. The σPERCASE cross section presented on the summary tables, was calculated using the MTBF method at 95%.

Table 8-1. Summary of OPA4H199-SP SET Test Condition and Results

Run #	Unit #	ION	LET_{EFF} (MeV × cm^2/mg)	Distance (mm)	FLUX (ions × cm^2/mg)	Fluence (Number ions)	Temperature (°C)	# of Long Events	# of Short Events
20	6	^{141}Pr	65	50	1.15×10^5	1.10×10^7	25	67	161
33	6	^{109}Ag	51	75	1.08×10^5	9.95×10^6	25	54	265
34	6	^{109}Ag	47	40	1.06×10^5	9.96×10^6	25	29	272
41	6	^{84}Kr	32	75	1.09×10^5	1.00×10^7	25	31	277
42	6	^{63}Cu	19	30	1.01×10^5	9.97×10^6	25	24	246
49	6	^{40}Ar	8	30	1.01×10^5	1.00×10^7	25	14	95
50	6	^{20}Ne	3	30	1.17×10^5	1.00×10^7	25	3	21

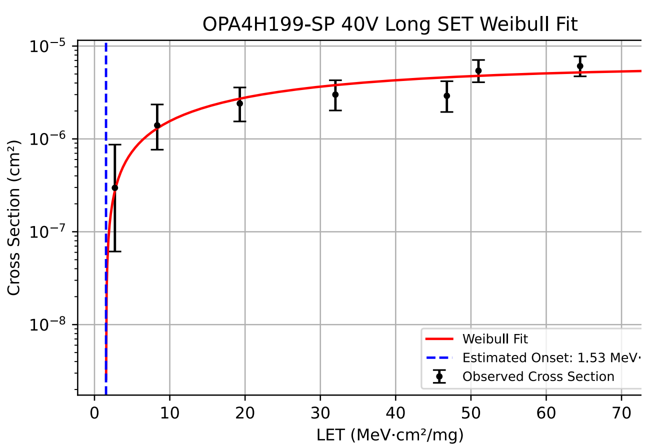

Figure 8-1. OPA4H199-SP Long SET Cross Section and Weibull-Fit

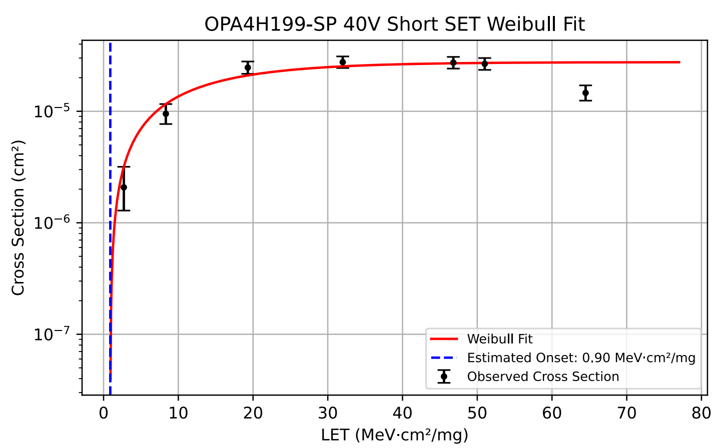

Figure 8-2. OPA4H199-SP Short SET Cross Section and Weibull-Fit

$$\sigma = \sigma_{SAT} \times \left(1 - e^{\left(\frac{LET - Onset}{W}\right)^{S}}\right) \quad (1)$$

Table 8-2. Weibull-FIT Parameters for DC Test

Parameter	Long	Short
Onset (MeV-cm^2/mg)	1.53	0.90
σ_{SAT} (cm^2)	6.09 × 10^{-6}	2.76 × 10^{-5}
W	31.23	13.14
s	0.94	1.06

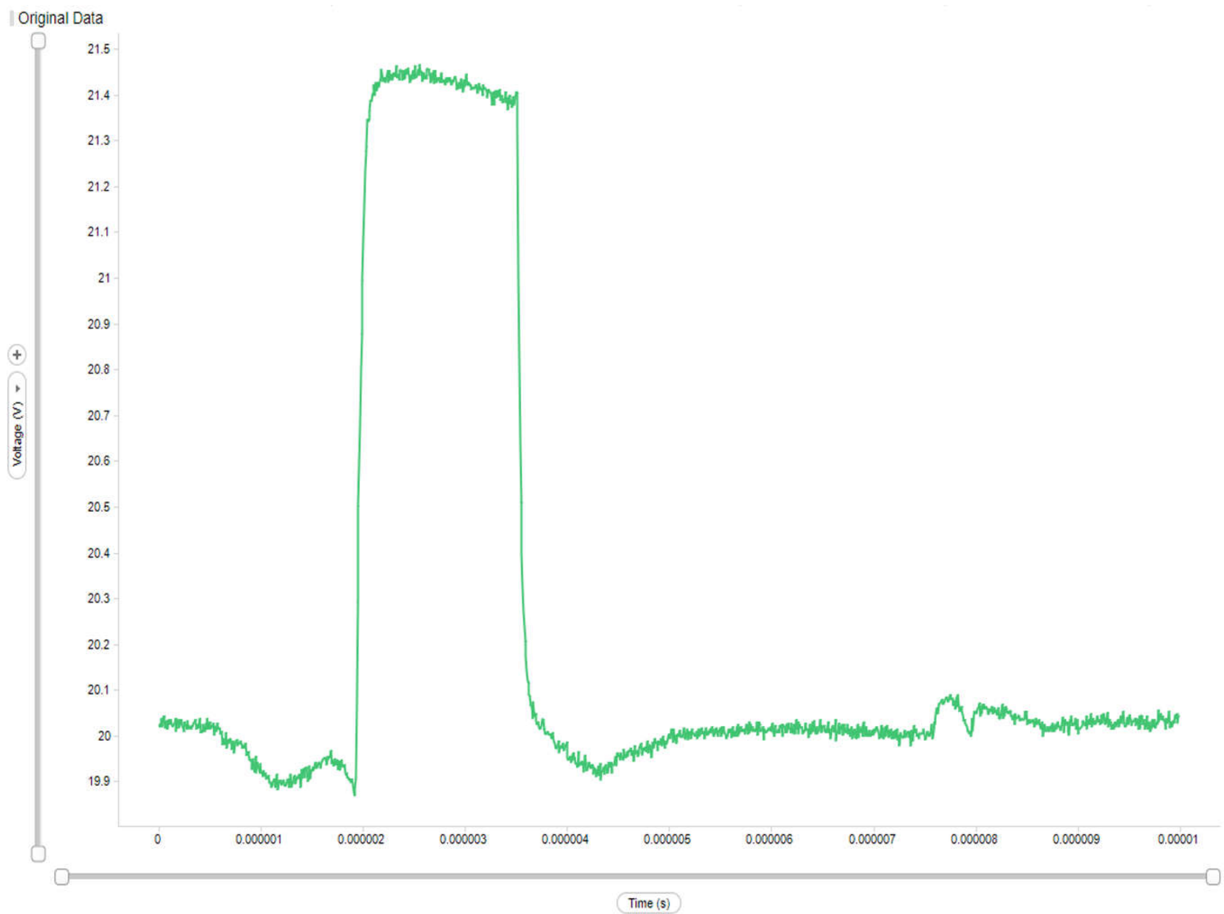

Figure 8-3. OPA4H199-SP Long SET Event Example (up)

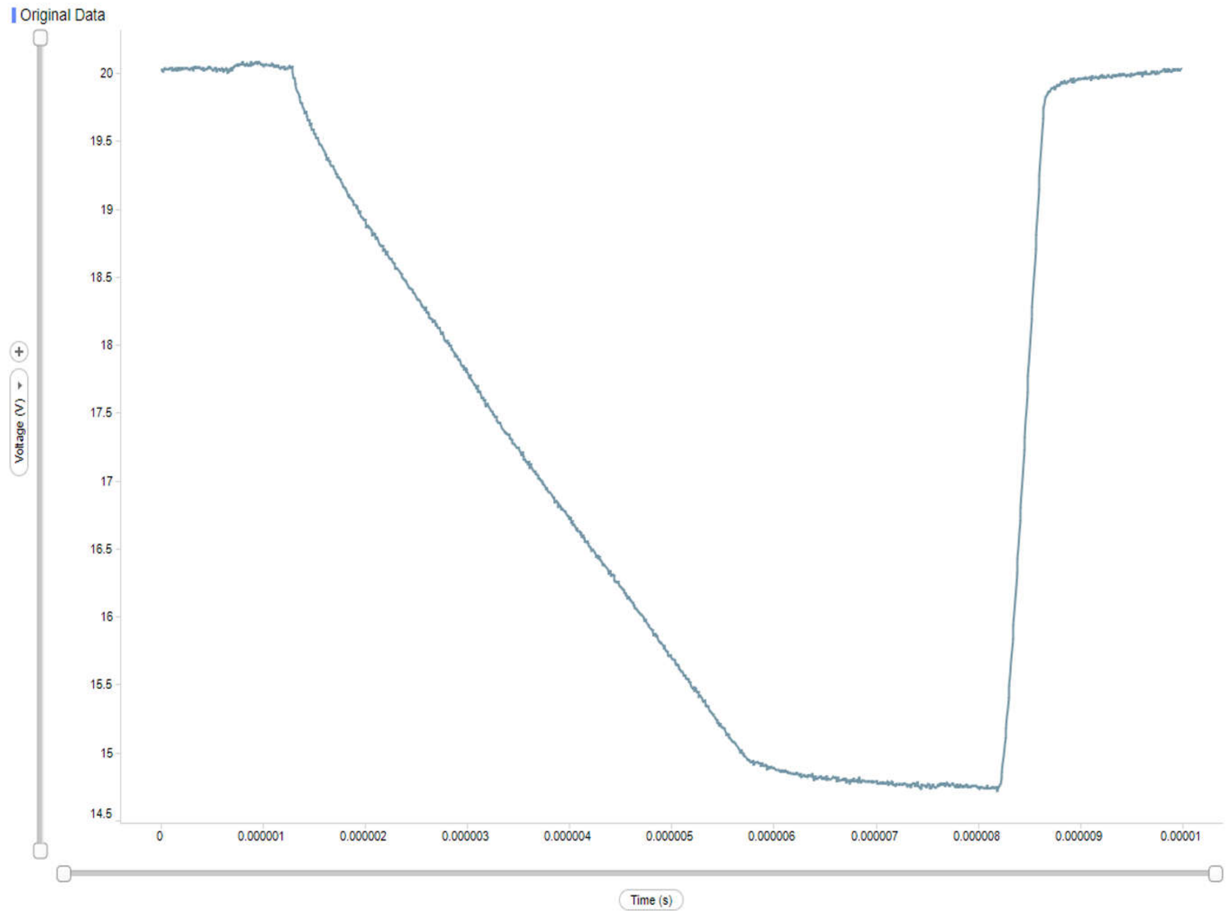

Figure 8-4. OPA4H199-SP Long SET Event Example (down)

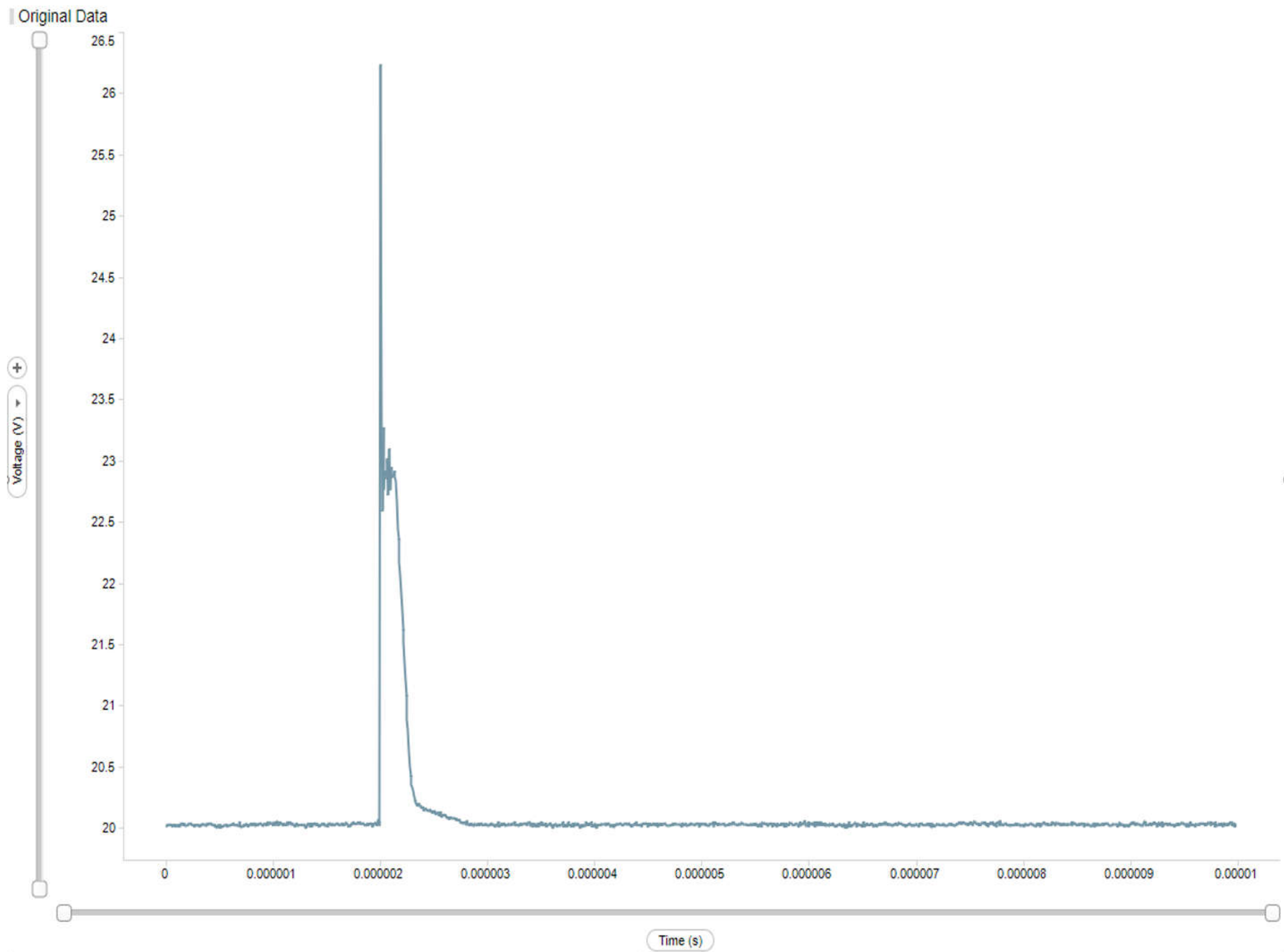

Figure 8-5. OPA4H199-SP Short SET Event Example (up)

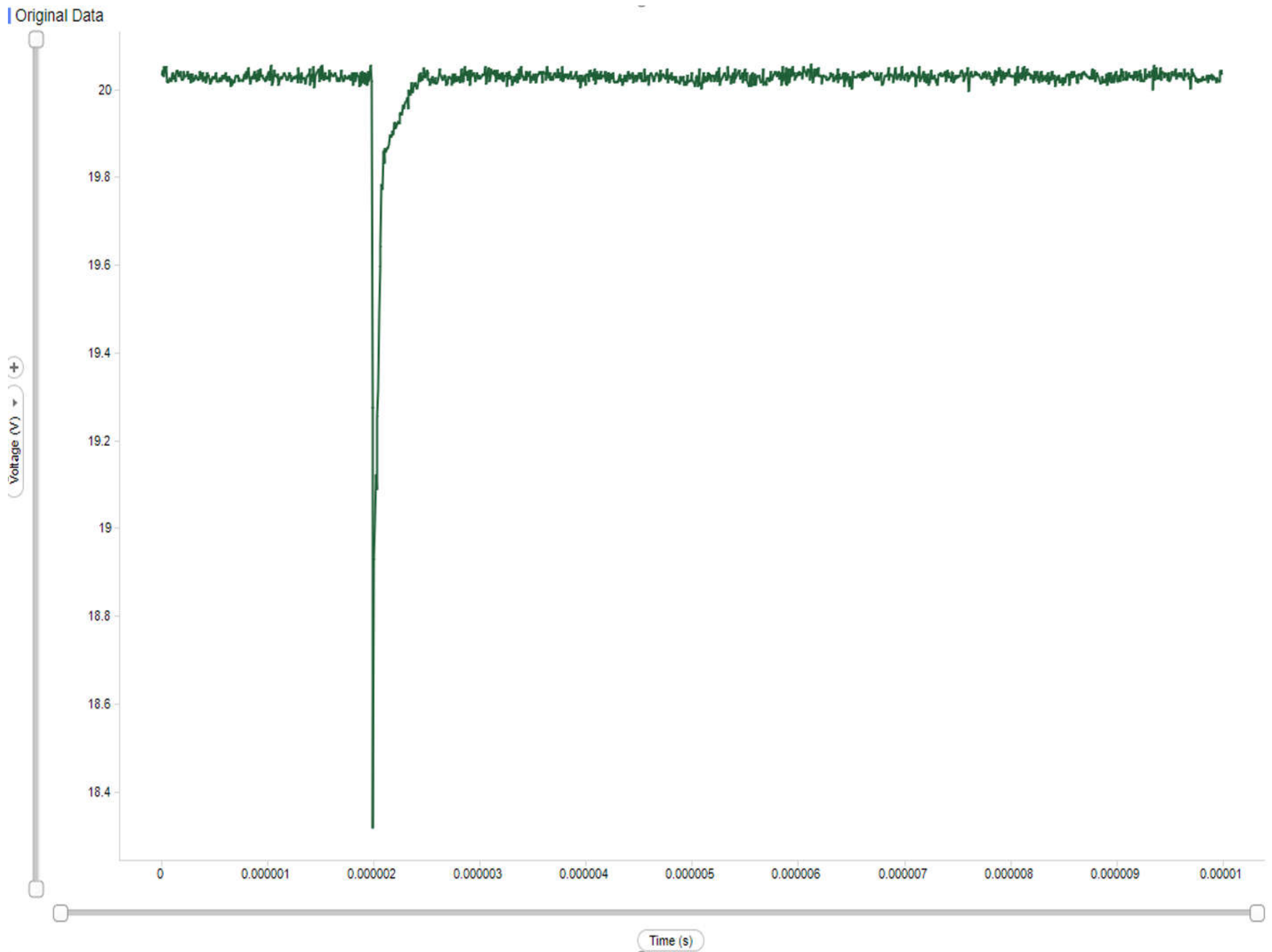

Figure 8-6. OPA4H199-SP Short SET Event Example (down)

9 Event Rate Calculations

Event rates were calculated for LEO (ISS) and GEO environments by combining CREME96 orbital integral flux estimations and simplified SEE cross-sections according to methods described in *Heavy Ion Orbital Environment Single-Event Effects Estimations*. Assume a minimum shielding configuration of 100mils (2.54mm) of aluminum, and *worst-week* solar activity (this is similar to a 99% upper bound for the environment). Using the 95% upper-bounds for SEL and SET the event rate calculations for SEL and SET are shown on Table 9-1 and Table 9-2, respectively. Note the onset LET_{EFF} for the long and short SET testing was estimated using Figure 8-1 and Figure 8-2.

Table 9-1. SEL Event Rate Calculations for Worst-Week LEO and GEO Orbits

Orbit Type	Onset LET_{EFF} (MeV-cm^2/mg)	CREME96 Integral FLUX (/day/cm^2)	σSAT (cm^2)	Event Rate (/day)	Event Rate (FIT)	MTBE (Years)
LEO (ISS)	65	1.19×10^{-4}	8.20×10^{-8}	9.72×10^{-12}	4.05×10^{-4}	2.82×10^{8}
GEO		3.40×10^{-4}		2.79×10^{-11}	1.16×10^{-3}	9.83×10^{7}

Table 9-2. Long SET Event Rate Calculations for Worst-Week LEO and GEO Orbits

Orbit Type	Onset LET_{EFF} (MeV-cm^2/mg)	CREME96 Integral FLUX (/day/cm^2)	σSAT (cm^2)	Event Rate (/day)	Event Rate (FIT)	MTBE (Years)
LEO (ISS)	1.53	8.39×10^{2}	7.74×10^{-6}	6.49×10^{-3}	2.71×10^{5}	4.22×10^{-1}
GEO		8.94×10^{3}		6.92×10^{-2}	2.88×10^{6}	3.96×10^{-2}

Table 9-3. Short SET Event Rate Calculations for Worst-Week LEO and GEO Orbits

Orbit Type	Onset LET_{EFF} (MeV-cm^2/mg)	CREME96 Integral FLUX (/day/cm^2)	σSAT (cm^2)	Event Rate (/day)	Event Rate (FIT)	MTBE (Years)
LEO (ISS)	0.9	2.75×10^{3}	1.71×10^{-5}	4.70×10^{-2}	1.96×10^{6}	5.83×10^{-2}
GEO		3.38×10^{4}		5.77×10^{-1}	2.40×10^{7}	4.75×10^{-3}

10 Summary

The purpose of this study was to characterize the effect of heavy-ion irradiation on the single-event effect (SEE) performance of the OPA4H199-SP operational amplifier. Heavy-ions with LET_{EFF} = 65MeV·cm^2/mg were used for the SEE characterization campaign. Flux of approximately 5 × 10^4 ions/cm^2 × s and fluences of approximately 10^7 ions/cm^2 per run were used for the characterization. The SEE results demonstrated that the OPA4H199-SP is free of destructive SEL SET up to LET_{EFF} = 65MeV·cm^2/mg across the full electrical specifications. CREME96-based worst-week event-rate calculations for LEO(ISS) and GEO orbits for the DSEE and SET are presented for reference.

A Total Ionizing Dose from SEE Experiments

The production OPA4H199-SP is rated to a total ionizing dose (TID) of 100krad(Si). In the course of the SEE testing, the heavy-ion exposures delivered approximately 10krad(Si) per 10^7 ions/cm^2 run. The cumulative TID exposure was controlled below 100krad (Si) per unit. All six OPA4H199-SP devices used in the studies described in this report were fully-functional after the heavy-ion SEE testing was completed.

B References

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